Evaluation of the environmental impacts of suckler calf-to-beef mixed crop-livestock farms in northern Italy: A farm-based study

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Highlights

- *Study of 11 farms for two years.*
- *High relevance of purchased feeds on environmental impacts.*
- *Productive and reproductive performances are key points in reducing environmental impacts.*
- *Importance of the valorisation of farm crop surfaces to satisfy animals' needs.*

Abstract

The issue of the environmental impacts of beef production has been extensively debated in recent years. However, the research on this theme has mainly been based on farm-model studies with limited attention to contribution analysis of impact categories and aspects linked to cropping systems and feed self-sufficiency in mixed crop-livestock farms. This study evaluated the cradle-to-farm gate environmental impacts of mixed-crop livestock farms rearing the Piedmontese beef breed and suckler calf-to-beef operations in Northwest Italy. Data have been collected from detailed on-farm questionnaires, field books, and invoices of 11 farms over two years (2017-2018). The environmental impacts have been evaluated in terms of land occupation (LO, m^2/year), global warming potential (GWP, kg CO_2-eq), acidification potential (AP, g SO_2-eq) and non-renewable cumulative energy demand (CED, MJ), using life cycle assessment methodology. The functional unit considered was one kilogram of live weight produced at the farm gate. The Piedmontese beef production system showed comparable average environmental impacts with those found in other studies, even though high variability was observed in the studied farms. The GWP averaged 15.7 kg of CO_2 eq/kg LW and ranged from 12.1 to 17.6 kg of CO_2 eq/kg LW. The CED, LO and AP were on average 62.4 MJ/kg LW, 18.5 m^2/y/kg LW and 305 g SO_2 eq/kg LW, respectively. Differences in environmental impacts and GWP contribution analysis were mainly due to differences in cropping system management strategies and the consequent levels of feed self-sufficiency. A positive effect of high fertility and animal productivity was observed on the GWP (r=0.62; P<0.01), highlighting the importance of improving efficiency of these aspects for the reduction of emissions. From the contribution analysis of impact categories, the high cost of purchased feeds (in particular protein feeds), transport, and mineral fertilizers for feed production were highly relevant. However further research is needed to confirm these findings.

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See online Appendix for additional materials.

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Introduction

The global population is expected to grow to 9.5 billion people by 2050 and this increase will be accompanied by an increase in the demand for animal products, including beef (Gerber *et al*., 2013). It has been estimated that the livestock sector is responsible for producing approximately 14.5% of all human-induced greenhouse gas (GHG) emissions (de Vries and de Boer, 2010; Gerber et al., 2013), with the beef sector being considered one of the main contributors (Legesse et al., 2016), accounting for 41% of all the livestock-related emissions (Gerber et al., 2013). Moreover, other than GHG emissions and climate change, concerns about beef production are represented by the high use of available resources, often in competition with human food, and by the risk of pollution linked to the progressive intensification of the production systems that has characterized this sector in recent decades (Capper, 2011).

Several methodologies have been applied to evaluate the environmental impacts of livestock systems (Lebacq et al., 2013) with the life cycle assessment (LCA) methodology (ISO, 2006a, 2006b; Finnveden et al., 2009; de Vries and de Boer, 2010; Lebacq et al., 2013) being the most widespread method used. The environmental impacts of beef production systems show different results (ranging from 8.6 to 35.2 kg CO_2 eq/kg live weight (LW); de Vries et al., 2015) with differences being mainly due to inherent characteristics of different production systems, although the boundary systems, assessment methods and data collected also play key roles in the obtained results (de Vries and de Boer, 2010; de Vries et al., 2015). Many studies have primarily been based on farm model data (Pelletier et al., 2010; Capper, 2012; Rotz et al., 2019) with models that describe a hypothetical farm, which is considered to be representative of the most widespread production system in a target country or region (Crosson et al., 2011). However, this approach may neglect the differences in agro-ecological and socio-economic contexts as well as the relationships and interdependencies among the system components that characterize real beef farms (de Boer et al., 2011). Furthermore, most of the published studies are focused on specialized beef production systems and seldom consider mixed livestock-cropping systems. The limited analysis of mixed systems suggests they may be more environmentally benign and economically viable due to the complementarities between crop and livestock activities (Ryschawy et al., 2012). Debaeke et al. (2017) and Veysset et al. (2014) showed that differences in cropping systems and crop management strategies can reduce GHG emissions of beef farms due to a reduction in N_2O and CH_4 emissions and an increase in carbon stock. Furthermore, Morel et al. (2016) highlighted that environmental impacts, energy consumption and land use of suckler beef production systems were affected by the adoption of different cropping systems and management strategies. Bonnin et al. (2021) previously analysed the global warming potential and economic performances of beef production in Northern Italy. Their work focused on the variability of GWP emissions and economic results between farms and between years, but other important environmental impact categories and their contribution analysis were neglected. Therefore, the aim of this study was to analyse the main environmental impact categories of mixed livestock-cropping systems to examine which components determine the environmental impact. To achieve this goal, detailed on-farm data collection over a two-year period was conducted on 11 Piedmontese beef farms.

Materials and methods

The present work represents an in-depth study of the work already published by Bonnin et al. (2021) using the data of two specific years (2017-2018) and focusing attention on a higher number of environmental impact categories and their detailed contribution analysis.

Farms characteristics

Data were collected over a two-year period (2017-2018) on 11 suckler calf-to-beef farms, rearing Piedmontese beef cattle. The farms were selected, from all of the whole-cycle farms in the region, on the basis of the farmers' willingness to participate in the survey. The studied farms were selected, in agreement with technicians from the Piedmont Regional Breeders Association (ARAP), who belong to the network of the Italian Breeders Association (AIA, www.aia.it) as being representative of the most widespread Piedmontese beef production and management strategies in Northwest Italy. All the sampled farms present the structural characteristics (herd size and management, forage system, labor organization) usually found in Northwest Italy for Piedmontese beef breed farms (22 to 177 ha and 86 to 387 LU) (Anaborapi, 2019), but are also characterized by a certain variability, in terms of farm size and number of reared animals. All the farms adopted conventional agronomic techniques: cereal grains were sown on fields that underwent conventional tillage practices (plowing, disc harrowing and rotary arrowing), were fertilized with both farm manure and mineral fertilizers, received at least one herbicide treatment and if necessary one phytosanitary treatment and, in the case of corn, fields were watered from 3 to 5 times per season. Meadows on the other hand were fertilized with only farm manure and were managed under conventional haying practices (mowing, tedding 2 or 3 times, swathing and bailing), meadows were cut from 3 to 4 times per season and in some cases the last cut was collected as fresh grass for cows or directly grazed. In some farms if irrigation water was available meadows were irrigated from 3 to 6 times.

The farms typically conduct cow-calf operations and the intensive fattening of Piedmontese farm-born calves and are small- to medium-sized family farms with grass and mixed crop systems for beef production (Bonnin et al., 2021). The sampled farms were mainly located in the flatlands (average altitude 375 m above sea level) of the Cuneo, Turin, and Asti provinces, where most of the Piedmontese beef population is reared (Anaborapi, 2019), and covered a wide range of pedoclimatic and resource availability conditions (availability of irrigation water, soil fertility and land availability) that characterize Piedmontese beef farms in Northwest Italy. The main animal production systems on the farms was represented by bulls, steers, and heifers, which were reared intensively on a diet based on large amounts of concentrates (mainly on-farm grown corn grains) and grass hay as a roughage source. The main protein source was soybean meal, and the use of genetically modified soybean meal was allowed. Suckler cows and calves were usually kept in confinement for the whole year and were fed a diet based on conserved forages, even in some farms where they were kept at pasture for the grazing season (Bonnin et al., 2021).

Life cycle assessment

The life cycle assessment (LCA) methodology adopted refers to the ISO 14040 and ISO 14044 standards (ISO 2006a, 2006b) and was organized in four distinct phases: i) definition of the goal, scope, and system boundaries; ii) life cycle inventory analysis; iii) life cycle impact assessment; iv) life cycle interpretation.

Definition of the goal and system boundaries

The system boundaries of the analysed beef production systems concerned a cradle-to-farm gate analysis by means of an attributional approach. All the farm inputs (*i.e.* off-farm breeding animals and calves, purchased feeds and bedding materials, fuels, fertilizers, seeds, pesticides, plastic and machinery) and outputs (*e.g.* emissions to the air, soil and water, meat, forages and cereals sold to the market) were considered (Figure 1). The transport of off-farm feeds and bedding materials and the transport associated with the transfer of fuels, fertilizers, seeds and imported calves were also included in the assessment. The farm structures and veterinary drugs were not taken into account (Bonnin *et al*., 2021). The considered functional unit was one kilogram of live weight (LW) (considering finished bulls and heifers, culled cows and weanlings sold to other farmers as breeding animals) produced on the farm at the farm gate. The specific emissions for beef production (enteric methane, GHG gases from manure storage and urine and faeces deposition during grazing, purchased feedstuffs, bedding material and related transports) were entirely allocated to beef. On the other hand, emissions not directly attributable to beef (mineral fertilizers, seeds, fuel, electricity *etc*.) were allocated, through an economic approach to meat and cereal grains and forages produced by the farm and sold to the market (*e.g*. 'non-specific' emissions were divided between all the farm outputs, that is, cattle, forages, and grains, according to their weighted percentage on the farm incomes). The economic approach was also considered for the allocation between the main product and by-products for farm inputs as previously reported by Bonnin *et al*. (2021).

Life cycle inventory analysis

The primary data were obtained from 11 farms for the years 2017 and 2018. Data covering herd composition, livestock production systems, livestock feed management, crop cultivation and manure management were collected from on-farm detailed questionnaires and were complemented with all the registered data available on the farms (field books, invoices, yearly sheet reports of the Piedmontese Cattle Breeders Association (Anaborapi). All the data concerning farm inputs (purchased feeds, bedding materials, fertilizers, agrochemicals, seeds, plastics, electricity, fuel, oil, and lubricants) and farm outputs (kg of LW sold, forages and cereal grains sold) were obtained from the analysis of all the farm invoices for the years 2017 and 2018. Furthermore, fuel, oil, and lubricants utilized in field operations by contractors were considered assuming average consumptions per hectare or work hours. All the main inventory data collected for the studied farms are reported in Table 1, data are presented as the average between the data of the two studied years. The feeds produced on each farm were assumed to be transported by tractor over an average distance of 1 km. The distance of the transport of the purchased feeds by truck was considered as the real distance from the farm to the manufacturing plant that provided the feed ingredients, or the feed mix to the farm. The same criterion was used for diesel, fertilizers and seeds purchased by the farmers. A distance of 200 km (mean distance from the study area and the main location of cereal production in the Po plain) for the raw feed materials produced in Italy and used by feed mill companies (corn, barley, sugar beet, wheat, soybean, and relative by-products) was considered. Voyages by ship to the closest Italian harbour and then a journey by truck to the feed mill plant were considered for other feedstuffs. The emission factors for the data on the production of seeds, plastics, fertilizers, pesticides, purchased feeds and bedding materials, tractors, and agricultural machines as well as for transport, were obtained from the Ecoinvent (Ecoinvent Center, 2015) and Agri-footprint (Blonk Agri-footprint 2014) databases contained in the SimaPro software (9.0.0.35 PhD PRé Consultants). Two databases were used as some information were not available only in one of the two databases. The practice of mixing different databases for secondary data has been used in other works (Nguyen *et al*., 2010; Berton *et al*., 2017; Bragaglio *et al*., 2018). The main processes used in the analyses were chosen within the categories of fuels, energy, transformation, lubricants (from Ecoinvent database), and animal feed, plant pro-

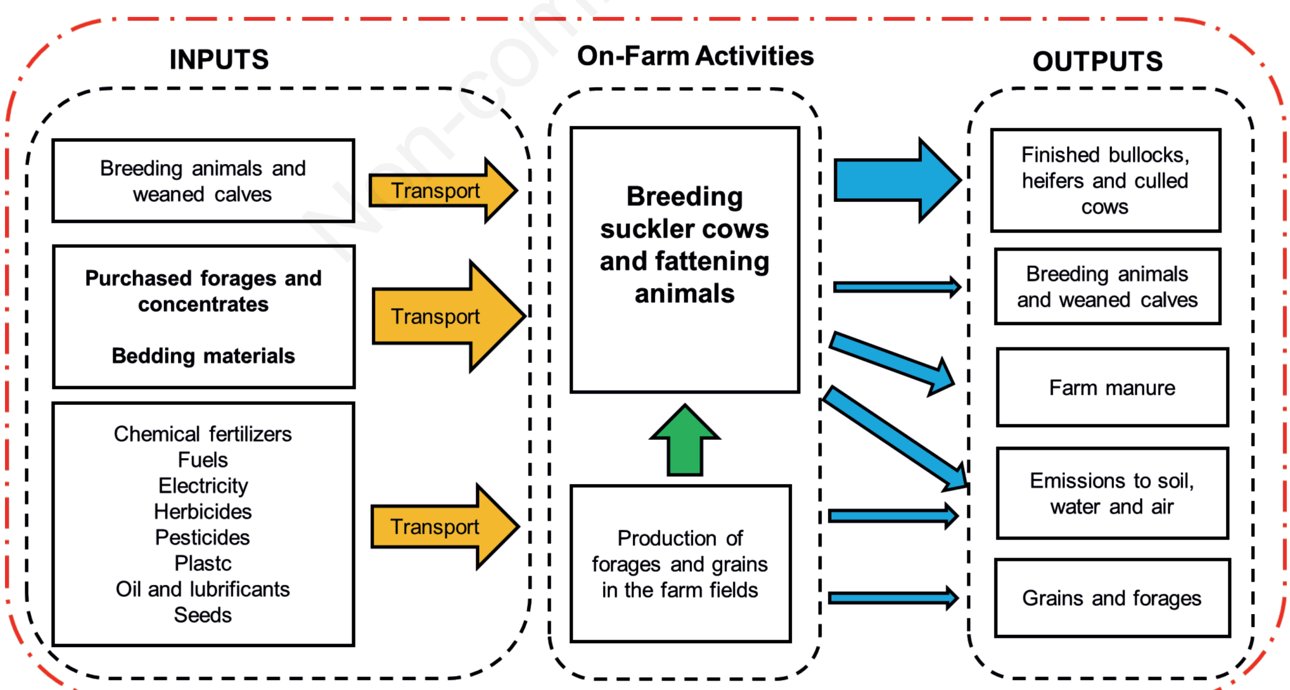

Figure 1. Life cycle assessment system boundaries of the studied farms.

duction, plant oils, plant seeds, pesticides and fertilizers (from Agri-footprint).

The total on-farm emissions related to enteric methane, manure storage and management, chemical or organic fertilization of the farm fields and deposition of urine and feces during grazing were calculated according to the Intergovernmental Panel on Climate Change (IPCC) methodology (IPCC, 2019a, 2019b).

Impact assessment

Among the LCA categories for the evaluation of environmental impacts the following were chosen: global warming potential (GWP), acidification potential (AP), land occupation (LO), non-renewable cumulative energy demand (CED), Human carcinogenic ecotoxicity, terrestrial and freshwater ecotoxicity. The GWP, CED, Human carcinogenic, Terrestrial and Freshwater ecotoxicity impact categories have been chosen as these are the categories of main interest for stakeholders according to the weighting factors proposed by Gloria *et al*. (2007), or because being of high interest for the livestock sector (LO and AP) (de Vries and de Boer, 2010; de Vries *et al*., 2015). The GWP was assessed using the Intergovernmental Panel on Climate Change (IPCC, 2013) (100 y, v1.03) methodology as this is the major assessment method used in LCA studies on beef production systems. Furthermore, it has also been chosen for its high reliability, its global scale of validity and for methodological uniformity, since on-farm emissions were calculated according to the IPCC methodology (IPCC, 2019a, 2019b). The CED was evaluated with the CED (v 1.11) methodology, according to Frischknecht *et al*. (2007). The AP, human carcinogenic ecotoxicity, terrestrial ecotoxicity and freshwater ecotoxicity were assessed using the ReCiPe Midpoint H 2016 (Huijbregts *et al*., 2017), LO has instead been assessed using the ReCiPe Midpoint H 2008 version (Goedkoop *et al*., 2009). The ReCiPe assessment method has been chosen because it is an updated and extended methodology representative for the global scale which includes a high number of midpoint impact categories (not considered by the IPCC 2013 methodology) and a hierarchical perspective with regards to a 100 years-time horizon.

Farm nitrogen balance

The farm nitrogen (N) balance was calculated as the difference between total nitrogen inputs and outputs at the farm-scale, with results presented on a per-ha basis (Oenema *et al*., 2003; Gourley *et al*., 2012). Nitrogen inputs considered were: the N content of the purchased fertilizers, the amount of purchased feeds multiplied by their N contents, according to INRA (2007), and the N fixation of alfalfa and mixed meadows, according to Borreani *et al*. (2003). For soybean N fixation the values reported by Goss *et al*. (2002) were considered. Nitrogen outputs considered were: the N outputs from beef cattle sold (the amount of live weight sold, multiplied by an average N content according to FAO, 2018), the N exported with the crops sold (INRA, 2007) and the N exported with manure, considering an average N content of 0.4% as reported by Tabacco *et al*. (2018).

Energy and protein self-sufficiency

The approach proposed by Tabacco *et al*. (2018) and Bonnin *et al*. (2021) was used to calculate the energy and protein self-sufficiency at a farm scale. The nutrient requirements of a beef herd for metabolizable energy (ME), crude protein (CP) and dry matter (DM) intake were calculated relative to the average daily gains and maintenance requirements for calves and fattening animals. The nutrient requirements of suckler-cows were calculated relative to their average milk production and quality, pregnancy and maintenance requirements, using version 6.1 of the CNCPS model (van Amburgh *et al*., 2015). The energy and protein self-sufficiency of each farm was calculated as the difference between the nutrient requirements of the beef herd and the nutrients supplied by the purchased feedstuffs (cereal grains, by-products, and forages), as obtained from the farm invoices. The ME and CP contents of the purchased feedstuffs were obtained directly from the feed labels or according to INRA (2007).

Statistical analysis

Data of the farm feed self-sufficiency, N balance and environmental impacts were analysed, with descriptive statistics, using the

Table 1. Main inventory data collected in the studied farms.

Parameter	Unit	Farm 1	2	3	4	5	6	7	8	9	10	11	Mean	SD
WU	No.	2	2	1	2	3	3	2	1	1	4	4	2.3	1.1
UAA	ha	34.2	61.1	23.3	24.2	74.5	76.3	22.1	38.1	34.7	97.3	177.2	60.3	46.3
Double cropped area	% UAA	6.2	8.2	0	45	48.8	0	38.6	0	35.1	7.8	10.7	18.2	19.4
Livestock units	No. of LU	108	164	86	141	183	133	117	90	236	321	387	178.7	97.9
Stocking rate	LU/ha	3.2	2.7	3.7	5.8	2.5	1.7	5.3	2.4	6.8	3.3	2.2	3.6	1.7
Mortality rate	%	2	3.2	5.8	5.1	4	2.5	5.1	4.1	5.3	3.2	2.7	3.9	1.3
Calving interval	d	376	390	369	415	367	391	372	424	390	425	454	397.5	28.2
Age at slaughter	months	15	15	15	16	15	16	16	20	18	15	20	16.5	2.0
Weight at slaughter	kg	503	580	523	510	530	560	595	608	620	535	640	564.0	47.3
Animal output	kg LW/LU	309	278	294	302	281	211	281	363	274	240	221	277.6	42.7
Farm-born cattle sold/LU	No. heads/LU	0.58	0.51	0.53	0.48	0.51	0.38	0.54	0.57	0.42	0.43	0.31	0.48	0.08
Concentrates	kg/t LW	3269	4536	3577	5394	4539	6514	3795	5561	8654	5284	5410	5139	1518
Purchased Concentrates	kg/t LW	3098	3862	3577	5394	797	1410	1939	3765	3938	3005	4248	3185	1341
Mineral N fertilizers	kg/t LW	38	65	0	70	318	185	85	97	52	77	14	91.0	89.6
Fuel	L/t LW	184	210	190	203	578	778	387	267	178	359	177	319.2	196.7
Electricity	kwh/t LW	101	393	71	92	682	79	655	143	64	192	103	234.1	234.0

LW, liveweight; LU, livestock unit; UAA, utilized agricultural area; WU, working unit.

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R software (R 3.5.1. Lucent Technologies, Murray Hill, New Jersey). The R software was also used to analyse the correlations between some of the parameters studied evaluating the Pearson's correlation coefficient.

Results

The main inventory data collected in the studied farms are reported in Table 1. The studied farms were small to medium sized family farms (on average 2.3 WU) and were characterized by an intensive finishing period in confinement, with cattle fed a cereal-based diet. Suckler cows and calves were kept in confinement for the whole year on a diet based on conserved forages, except for two farms (Farm 1 and 11) in which they were kept at pasture for the grazing season. Figure 2 shows the average proportion of crops of the UAA of the studied farms. The cropping systems of the studied farms were mainly based on permanent or temporary meadows destined for hay production and on corn crop harvested as dry grain or whole-plant silage. Some farms substituted corn for grain with the whole-ear corn silage. The cultivation of winter cereals destined for whole-plant silage to feed suckler cows or for grain production for sale was widespread. Double-cropping was practiced on most of the studied farms as shown in Figure 2 and Table 1.

The average DM yield per ha was on average 11.3 t DM (Table 2), with the main contribution being represented by permanent and temporary meadows, corn for grain and whole-plant corn silage. The concentrate and forage self-sufficiency and the percentage of farm-grown forages and grains employed on-farm are reported in Table 2. Several farms (Farm 1, 2, 3, 4, 7, 8, 9, 10 and 11) bought large amounts of concentrates on the market. The concentrate self-

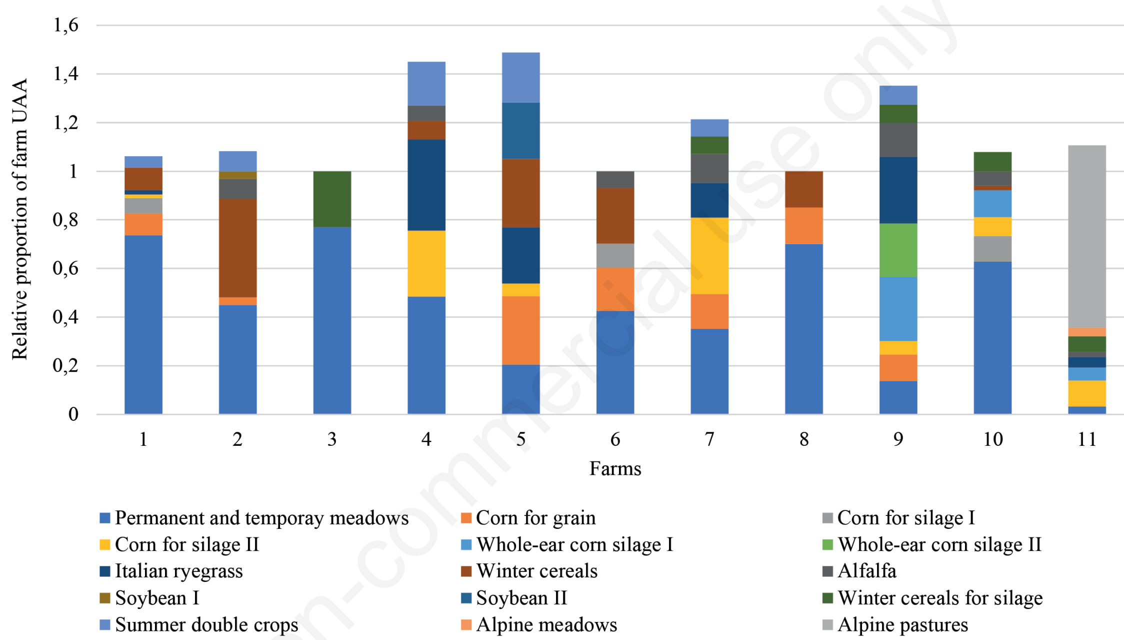

Figure 2. Average proportion of crops on the utilized agricultural area (UAA) of the studied farms (values higher than 1 means the presence of double cropped area).

Table 2. Farm self-sufficiency, average yields and on-farm employment rates of grains and forages.

Parameter	Farm 1	2	3	4	5	6	7	8	9	10	11	Mean	SD
Average DM yield (t DM/ha)	12.2	9.8	13.2	15.5	10.9	8.3	14.2	9.7	16.1	10.3	4.2	11.3	3.4
Average crude protein yield (t CP/ha)	1.2	1.1	1.1	1.5	1.3	0.9	1.8	0.9	1.6	1.0	0.4	1.2	0.4
Average energy yield (GJ ME/ha)	83.9	67.1	90.9	138.1	83.2	62.8	149.1	65.0	131.0	91.1	31.7	90.4	35.9
Farm-grown cereal grains fed to cattle (%)	7.6	9.7	0.0	0.4	56.9	63.7	78.1	64.6	100	100	100	52.8	41.3
Concentrate self-sufficiency (%)	4.18	9.98	0.00	0.02	87.9	82.1	39.5	35.5	55.2	36.0	29.1	34.5	30.8
Farm-grown forages fed to cattle (%)	97,0	100	100	92.8	95.1	100	100	100	100	100	100	98.8	2.6
Forage self-sufficiency (%)	97.1	100	100	90.7	100	100	96.7	98.4	70.8	98.9	95.3	95.3	8.6
Energy self-sufficiency (%)	67.6	67.3	55.2	60.8	94.2	93.9	83.7	62.6	58.1	6.6	60.6	71.0	14.1
Protein self-sufficiency (%)	68.0	75.1	62.2	63.9	89.9	92.5	76.5	56.5	52.5	60.6	63.8	69.2	13.0

SD, standard deviation; DM, dry matter; CP, crude protein; ME, metabolizable energy.

sufficiency was low on most of the studied farms, with Farms 1, 2, 3 and 4 being almost completely dependent on purchased concentrates, and only Farms 5 and 6 being able to satisfy more than 80% of their herd requirements. Forage self-sufficiency was on the other hand high on all the farms. Similar trends were found for protein and energy self-sufficiency with only Farms 5, 6 and 7 showing high levels of self-sufficiency. Table 3 reports the farm-scale nitrogen balance of the studied farms. The N balance was always positive, with a N surplus ranging from 31 to 268 kg N/ha. The main N inputs were represented by feeds and bedding materials (42.2%), mineral fertilizers (36.3%) and N fixation by legumes (21.5%), while the main outputs were represented by N content in live animals sold (57.9%) and in cereal grains and forages sold on the market (33.2%).

Animals were slaughtered on average at 16.5 months of age and 564 kg of weight. However, Farms 8, 9 and 11 slaughtered their animals at an older age and at a higher weight. Mortality rate averaged 3.9% with Farms 3, 4, 7 and 9 being characterized by a mortality rate higher than 5% while Farms 1, 6 and 11 showed lower mortality rates (around 2%). Herd fertility was on average good with a mean value below 400 days for the calving interval indicator. Farms 1, 5 and 7 showed calving interval values very close to the optimum value of 365 days but several farms (4, 8, 10 and 11) were characterized by poor herd fertility performances (calving intervals around 420 days). The studied farms were suckler cow-to-beef farms, therefore the purchase of cattle from other farms was low and limited in almost all farms to breeding animals even if some farms bought some additional calves for fattening to replace dead calves. Animal output per LU averaged 277 kg LW/LU with low values for Farms 6 and 11 (around 215 kg LW/LU) and values above 300 kg LW/LU for Farms 1, 4 and 8. A similar trend was found for the number of farm-born cattle sold per LU.

The cradle-to-farm gate life cycle global warming potential (GWP), land occupation (LO), non-renewable cumulative energy demand (CED), acidification potential (AP), terrestrial, freshwater and human carcinogenic ecotoxicity of the studied farms are reported in Table 4. A mean GWP value of 15.7 kg of CO_2 eq/kg LW was observed in the present study, but high variability was found, with values ranging from a minimum of 12.8 kg CO_2 eq/kg LW for Farm 5 to a maximum of 18.6 CO_2 eq/kg LW for Farm 11. In Table 1S are reported the GWP values of the studied farm using the economical or mass approach. The two methods were different, with higher values using economical approach (on average 15.7 kg CO_2 eq/kg LW) than mass approach (on average 8.6 kg CO_2 eq/kg LW). The mean CED value in the studied farms was 62.4 MJ/kg LW, with Farm 1 showing the lowest value and Farm 9 the highest (51.3 and 69.4 MJ/kg LW respectively). In terms of LO the values found ranged from 8.5 m^2/y/kg LW for Farm 7 to 67.0 m^2/y/kg LW

Table 3. Nitrogen (N) balance (kg/farm or otherwise specified) at the farm scale for the studied farms.

Parameter	Farm 1	2	3	4	5	6	7	8	9	10	11	Mean	SD
N inputs													
Mineral N	1251	2805	0	3010	16,137	5074	2793	3168	3400	5919	1241	4073	4338
N fixation	1008	2729	720	904	1548	2745	1240	1068	1488	3983	6744	2198	1812
N from feeds and bedding materials	2749	3175	2465	4034	1440	910	1693	2966	7209	8196	8353	3926	2718
Total N input	5007	8710	3185	7948	19,125	8728	5726	7202	12,097	18,098	16,338	10,197	5458
Total N input (kg/ha)	146.7	142.6	136.8	328.0	256.8	114.4	259.0	189.0	348.5	186.0	35.7	195	95
N outputs													
N in crops sold	946	3553	0	481	3937	1654	162	601	0	0	0	1030	1439
N in milk	0	0	0	0	0	0	0	0	0	520	0	47	157
N in meat	801	1096	608	962	1231	673	783	784	1466	1844	2051	1118	484
N in manure sold	0	0	0	0	207	0	216	0	1598	0	18	185	476
Total N output	1746	4649	608	1443	5374	2327	1161	1385	3064	2364	2069	2381	1469
Total N output (kg/ha)	51	76	26	60	72	31	53	36	88	24	5	47	26
N balance													
kg N/farm	3261	4061	2577	6505	13,751	6401	4565	5816	9033	15,734	14,269	7816	4708
kg N/ha	96	67	111	269	185	84	207	153	260	162	31	147	78

N, nitrogen; SD, standard deviation.

Table 4. Cradle to-farm gate life cycle global warming potential, land occupation, non-renewable cumulative energy demand, acidification potential, terrestrial, freshwater and human carcinogenic ecotoxicity of the studied farms.

Parameter	Farm 1	2	3	4	5	6	7	8	9	10	11	Mean	SD
GWP (kg CO_2 eq)	13.8	14.8	15.5	17.9	12.8	14.0	15.6	14.8	18.5	16.8	18.6	15.7	1.97
Non-renewable cumulative energy demand (CED) (MJ)	51.3	61.4	53.7	75.7	60.0	62.8	56.8	61.7	69.4	66.7	67.6	62.4	7.1
Land occupation (LO) (m^2/y/kg LW)	12.8	13.8	13.0	16.5	10.5	15.2	8.5	14.3	19.3	12.4	67.0	18.5	16.3
Acidification potential (AP) (g SO_2 eq)	230	290	317	334	240	286	287	252	348	368	410	306	56
Terrestrial ecotoxicity (kg 1,4 DCB)	6.95	8.37	9.89	12.15	4.04	4.53	6.95	5.29	12.65	9.05	11.40	8.30	3.02
Freshwater ecotoxicity (kg 1,4 DCB)	0.073	0.088	0.089	0.138	0.034	0.041	0.069	0.059	0.227	0.160	0.116	0.099	0.057
Human carcinogenic ecotoxicity (kg 1,4 DCB)	0.058	0.078	0.079	0.100	0.042	0.035	0.062	0.041	0.182	0.073	0.169	0.083	0.049

1,4 DCB, 1,4-dichlorobenzene; GWP, global warming potential; LW, liveweight; SD, standard deviation.

for Farm 11, while the average value was 18.5 m^2/y/kg LW. The average AP found in the present study was 305 g SO_2 eq/kg LW with variations from a minimum of 230 g SO_2 eq/kg LW for Farm 1 to a maximum of 410 g SO_2 eq/kg LW for Farm 11.

The contribution of the various GWP emission sources is reported in Figure 3. The most important GWP source was enteric methane (46.5), followed by purchased feeds (21.9%), nitrous oxide emissions from manure spreading and mineral fertilizer use (19.4%), CO_2 emissions related to farm activities for feed production (9.6%) and methane emissions from manure (2.6%). Farms 5, 6 and 7 showed low values for purchased feeds and high values for on-farm feed production (fuel and mineral fertilizers), whereas an opposite trend was observed for all the other farms. Most of the purchased concentrates used on the studied farms were protein feeds, whereas energy feeds (corn, whole-ear corn silage, and barley) and forages were generally produced on the farms (Figure 2). On average, the impact of the purchased protein feeds (soybean meal, sunflower meal, wheat bran, beans, and peas) accounts for 41% of the overall emissions for the purchased feeds (Figure 4). The emissions linked to the purchase of energy feeds (corn, barley, and wheat grains), forages and other feeds (beet pulp, wheat germ, molasses, fats, distillers, and vitamin and mineral supplements)

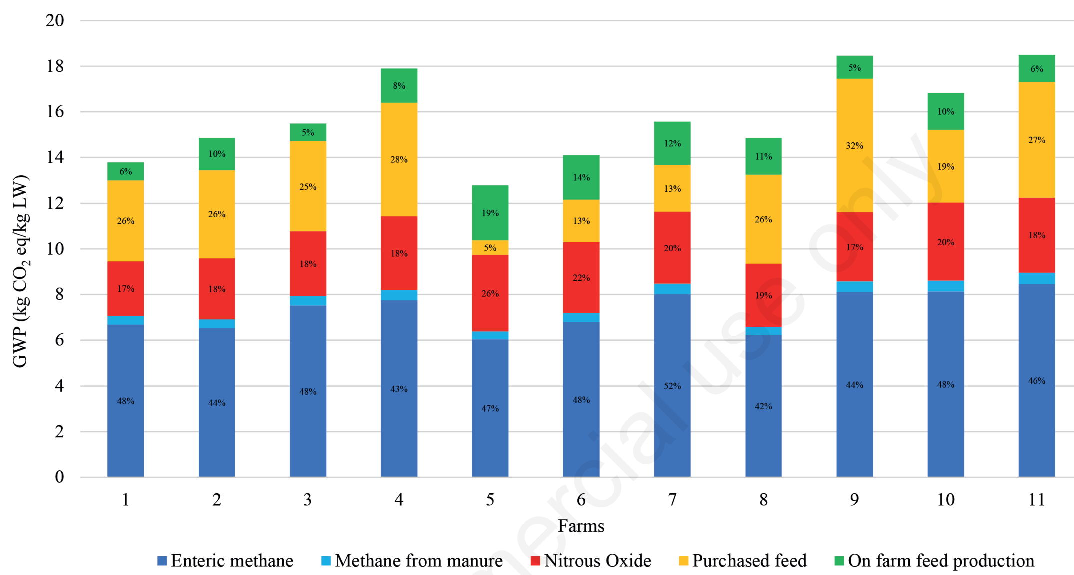

Figure 3. Contribution analysis of the different processes to the global warming potential (GWP) in the studied farms. LW, liveweight.

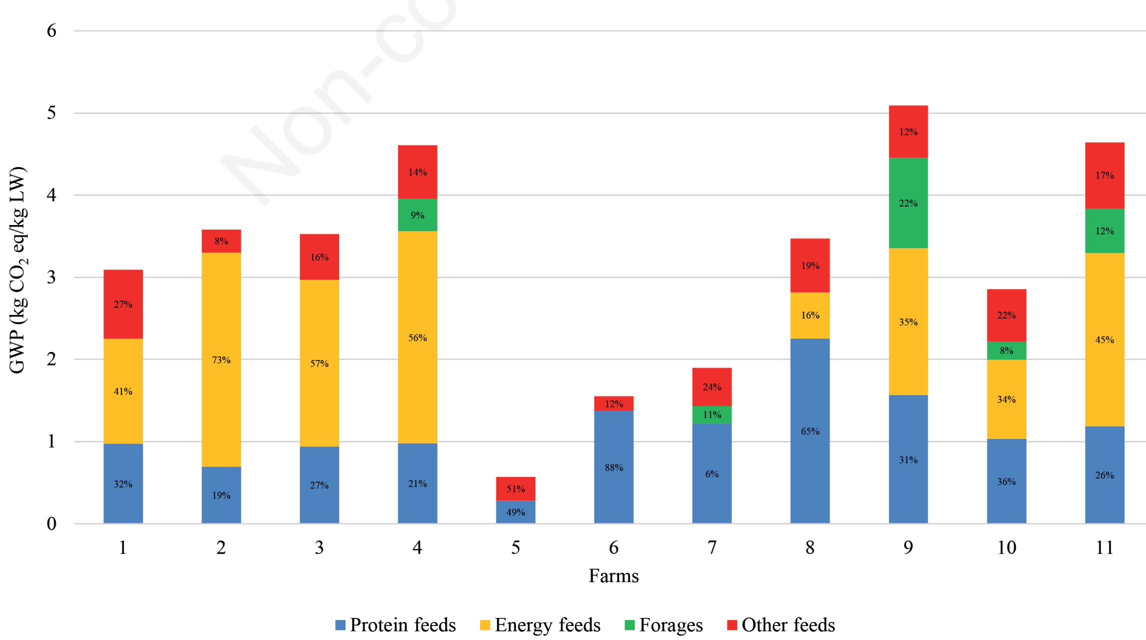

Figure 4. Contribution analysis of the global warming potential impacts (kg CO_2 eq/kg LW) by categories of purchased feed in the studied farms. LW, liveweight; GWP, global warming potential.

were 32.5%, 5.5% and 21% of the overall emissions for purchased feeds, respectively. Some differences between farms are shown in Figure 4 which reports the contribution analysis of GWP impacts by categories of purchased feeds per kg of LW produced. Farms 6, 7 and 8 showed the highest contribution of protein feeds, while Farms 1, 2, 3, 4, 5 and 10 showed the lowest impacts, whereas Farms 9 and 11 were intermediate. Figure 5 reports the contribution analysis of impacts by categories of the on-farm feed production. On average, the main impact categories were machinery and fuel employed for feed production (39.3%), transport of all farm inputs (19.9%) and mineral fertilizers (16.1%). Farms 5 and 6 showed the lowest value for transport and the highest for fuel and fertilizers. The consumption of electric energy did not represent a large part of the on-farm emissions, since it was mainly used for manure removal, milling cereals or for cooling sheds. On Farms 2, 5 and 7 these values were higher than the average since they employed electric power to pump water from wells to water crops.

The factors contributing to CED, LO, and AP are reported in Figure 1S, 2S, and 3S, respectively. Farms 1, 2, 3, 4, 8, 9,10 and 11 were characterized by a higher relevance of the purchased feeds on CED, followed by fuels, machinery, transport of farm inputs and mineral fertilizers. Farms 5, 6 and 7 on the other hand showed a lower relevance of purchased feeds and a higher relevance of fuels and fertilizers on the composition of CED. In the case of LO, the main contributor was farm area, which accounted for 53.1%, followed by the land required to grow the purchased feeds (45.6%), and other land requirements (land for farm buildings and for seed production). The contribution analysis of AP showed that the majority of AP was due to NH_3 emissions from manure management (87%), followed by purchased feeds (10%) and on-farm feed production (3%). The correlations between environmental impact indicators and technical efficiency indices are reported in Table 5.

A positive correlation was found between GWP and calving interval, concentrate consumption, purchased concentrate consumption and animal output (kg LW/ha). On the other hand, the number of heads of farm-born cattle sold per LU negatively correlated with all the environmental impact categories analysed (r= –0.781; –0.617; –0.586 and –0.704 with AP, CED, GWP and LO, respectively). Concentrate self-sufficiency positively correlated with mineral fertilizer and fuel use, and negatively correlated with purchased concentrate consumption. The use of mineral fertilizers negatively correlated with purchased concentrate consumption, while positive correlations between calving interval and LO, AP, and CED were found.

Discussion

The present work evaluated the environmental impacts of beef production on suckler calf-to-beef farms by means of an on-farm analysis. Data were collected over a two-year period with a detailed contribution analysis of the studied impact categories. Bonnin *et al*. (2021) previously analysed the GWP emissions and economic performances of suckler calf-to-beef production in Northern Italy, focusing attention on between year and farm variability. This study aimed to evaluate other important environmental impact factors and conduct a detailed contribution analysis of the impact categories, as these are rarely found in the published literature.

The cropping system of the studied farms was based on meadows, corn and winter cereals. The system focused on forage production for the herd while grains produced were mainly sold with neg-

Table 5. Correlations between environmental impact indicators and technical efficiency indices.

	AP	CED	GWP	Concentrate self-sufficiency	Concentrate consumption kg	Calving interval	Fuel L/t LW	Animal Output kg LW/ha	LO	Stocking rate	Min N kg/t LW	Farm-born cattle sold/LU	Purchased concentrates kg	Purchased concentrates kg/t LW
AP	1.000	-	-	-	-	-	-	-	-	-	-	-	-	-
CED	0.632*	1.000	-	-	-	-	-	-	-	-	-	-	-	-
GWP	0.892***	0.714*	1.000	-	-	-	-	-	-	-	-	-	-	-
Concentrate self-sufficiency	−0.192	0.052	−0.324	1.000	-	-	-	-	-	-	-	-	-	-
Concentrate consumption (kg)	0.722*	0.679*	0.724*	0.212	1.000	-	-	-	-	-	-	-	-	-
Calving interval	0.658*	0.638*	0.620**	−0.214	0.548	1.000	-	-	-	-	-	-	-	-
Fuel (L/t LW)	−0.325	−0.082	−0.545	0.831**	−0.208	−0.259	1.000	-	-	-	-	-	-	-
Animal output (kg LW/ha)	0.674*	0.504	0.852**	−0.385	0.573	0.458	−0.639*	1.000	-	-	-	-	-	-
LO	0.665*	0.342	0.551*	−0.177	0.523	0.703*	−0.283	0.684	1.000	-	-	-	-	-
Stocking rate	0.245	0.354	0.852*	−0.169	0.280	−0.189	−0.412	0.538	−0.216	1.000	-	-	-	-
Mineral N (kg/t LW)	−0.494	−0.014	−0.607	0.808**	−0.125	−0.322	0.802**	−0.531	−0.327	−0.317	1.000	-	-	-
Farm-born cattle sold/LU	−0.781**	−0.617*	−0.586**	−0.275	−0.726*	−0.585	−0.183	−0.412	−0.704*	−0.081	0.046	1.000	-	-
Purchased concentrates (kg)	0.839**	0.676*	0.876***	−0.378	0.784**	0.785**	−0.604*	0.779**	0.731*	0.231	−0.546	−0.613*	1.000	-
Purchased concentrates (kg/t LW)	0.504	0.501	0.713*	−0.803**	0.288	0.543	−0.827**	0.653*	0.360	0.384	−0.750**	−0.103	0.730*	1.000

Significant at: <0.001***, <0.01**, <0.05*. AP, acidification potential; CED, non-renewable cumulative energy demand; GWP, global warming potential; LO, land occupation; LU, livestock unit; LW, liveweight.

ative environmental consequences on the farm concentrate, energy and protein self-sufficiency. To increase feed production on the farm surfaces double-cropping was practiced on most of the studied farms, due to the availability of irrigation water, manure for crop fertilization, and climate conditions which allow winter and summer crops to be grown in the same year. Despite the high average DM yields per hectare, consistent with the values reported by Gislon *et al*. (2020) for cropping systems serving dairy farms in the Po plain in Italy, several farms needed large additional amounts of concentrates that were purchased on the market. This is particularly evident on farms with a high stocking rate (Farms 3, 4, 7 and 9) and on farms that grow cash crops (corn, wheat, and barley grains) which could otherwise be used to satisfy the nutritional requirements of the herd (Farms 1, 2 and 4). Data concerning the percentage of farm-grown grains effectively employed on farm as animal feed and not sold to the market are reported in Table 2. From the analysis of self-sufficiency, it emerged that the studied farms adopted two different strategies. Some farms (5 and 6) adopted a cropping system management aimed at maximizing the overall farm self-sufficiency (forages, cereal grains, and part of protein feeds), while other farms adopted cropping systems aimed at maximizing the forage self-sufficiency by designating most of their arable land for the production of cash crops, with most of the concentrates being purchased, leading to negative implications on the nutrient balance of the farms, as previously reported by Tabacco *et al*. (2018) for conventional cropping systems for dairy cows.

Liveweight and age at slaughter found in the studied farms were comparable to those found for the Piedmontese breed (Anaborapi, 2019), some farms slaughtered their animals at an older age (Farms 8, 9, 11), but this was counterbalanced by a higher weight at slaughter. Also the reproductive performances of the herd and calf mortality rates fall within the normal ranges reported for the Piedmontese breed (Anaborapi, 2019) with some farms being characterized by high efficiency levels and good performances for both aspects (Farm 1 and 5). Animal output and the number of heads of farm-born cattle sold per LU followed a similar trend and showed higher values in the farms characterized by a higher overall herd productivity (Farms 1, 5, 7 and 8).

It has been reported that GWP decreases as the production system intensifies in resources use and herd and pasture management. The average GWP value of 15.7 kg CO_2 eq/kg LW found in the present study is comparable with the findings of studies conducted in other countries with values ranging from 13.8 to 22.0 kg CO_2 eq/kg LW (Pelletier *et al*., 2010; Cullen *et al*., 2016; Alvarez-Hess *et al*., 2019; Costantini *et al*., 2021). Lower values of 13.1 and 13.2 kg of CO_2 eq were observed by Berton *et al*. (2017) for the production of bullocks on intensive farms in Italy with calves imported from France, and by Nguyen *et al*. (2012) for beef production in France, respectively. However, the aforementioned studies included carbon sequestration in permanent grasslands, while the present study did not. Higher values of 22.0 kg CO_2 eq/kg LW were found by Costantini *et al*. (2021) in semi-intensive system, especially when it occurs on pasture. The contribution analysis of the emission sources in the present study are in agreement with those of Bragaglio *et al*. (2018) who reported enteric emissions (48%) and feed inputs (34%) as the main sources. In the present experiment, emissions not directly attributable to beef were allocated, through an economic approach to meat and cereal grains and forages produced by the farm and sold to the market as previously reported by Bonnin *et al*. (2021). The GWP values were calculated using the economical or mass approach (Table 1S). The two methods were different, with higher values using economical approach than mass approach (15.7 *vs* 8.6 kg CO_2 eq/kg LW). These differences could occur because the live weight has lower mass but higher economic value than those of the other products, cereals in particular. Thus, economic allocation could be considered a suitable allocation method in beef systems, as previously reported by Nguyen *et al*. (2012). AP and LO average values found in the present study were similar to those reported by others for intensive systems (Berton *et al*., 2017; Bragaglio *et al*., 2018) but lower compared to those reported by Capper (2012) and Pelletier *et al*. (2010). The differences in terms of LO might be ascribed to the more intensive and confined cow-calf phase that characterizes the studied systems, to the high crop yields per hectare (resulting from corn and double-crops) observed on the studied farms, and to the high use of concentrates, leading to lower land requirements compared to pasture-based systems. The LO per unit of beef has been reported to be lower for concentrate-based systems compared to forage-based systems (de Vries *et al*., 2015). The AP is caused mainly by NH_3 emissions (Nguyen *et al*., 2012) which are highly influenced by climatic conditions, such as temperature and air velocity but also soil type (De Boer *et al*., 2002; Rotz *et al*., 2019), making it difficult to compare results from different studies.

The mean CED value in the present study is higher than the values reported by others (Pelletier *et al*., 2010; Berton *et al*., 2017). The primary reason for these differences in the current study could be due to suckler cows being kept at pasture and therefore those systems were characterized by low energy inputs. In the present study suckler cows were mainly kept indoors, with higher energy requirements for the production and transport of feeds as well as for manure management.

Analysing the contribution analysis of environmental impact factors, it emerged that enteric CH_4 represents more than 40% of GWP. This value agrees with those observed in studies conducted in the EU and in the US (Pelletier *et al*., 2010; Lesschen *et al*., 2011). Furthermore, GWP is highly influenced by the different cropping systems and feed self-sufficiency strategies adopted on-farm, as previously reported by Morel *et al*. (2016). In the present study, the farms characterized by high levels of feed self-sufficiency showed a lower amount of purchased feeds, and a higher level of on-farm feed production impacts on their GWP. On the other hand, farms characterized by low levels of feed self-sufficiency showed an opposite outcome with a high incidence of purchased feeds. When the feed contribution to GWP was considered, it emerged that farms classed as having higher feed and concentrate self-sufficiency levels had a higher protein feeds contribution to the GWP of their purchased feeds, as the production of all the energy concentrates and part of the protein ones took place on the farm. On the other hand, farmers that purchased almost all the concentrates showed a higher contribution by of energy feeds to GWP, as the main ingredients in concentrates for fattening beef are represented by energy feeds. Buying feeds on the market (especially concentrates) has been reported to have a higher environmental impact than producing them on the farm, mainly because of the emissions related to the transport of feeds and to changes in land use, which are particularly relevant for some feeds, such as soybean meal from South America (Garnett, 2009; Opio *et al*., 2013). In the present study the farms showing higher feed self-sufficiency levels showed lower GWP values. Positive correlations between the GWP and purchased concentrate consumption have been found in the present study, thereby highlighting the effect of purchased concentrates on the environmental impacts of beef production, as a result of LUC and transport-related emissions (Berton *et al*., 2018). The magnitude of the on-farm feed production emissions in the present study also appears to be closely linked to the amount of purchased feeds. The reason for this is that the higher the amount of feeds purchased, the lower the amount of inputs (fertilizers, fuels, seeds, and agrochemicals) that the farm needs to grow feeds on the farmland and the emissions related to on-farm feed production are therefore lower. Farms characterized by high feed self-sufficiency (Farms 5 and 6) showed the lowest contribution from transports and the highest for fertilizers, fuel, and machinery when the contribution analysis of on-farm feed production was considered. This is also confirmed by the positive correlation found between feed self-sufficiency and fuel and mineral N fertilizer use (r=0.83 and 0.81 respectively). Our results are in agreement with Morel *et al*. (2016) that reported that a high self-sufficiency level led to higher requirements of fuel and mineral fertilizers.

The contribution analysis of the impacts of CED by categories showed a lower importance of purchased feeds and a higher incidence of fuels, machinery, transports, and mineral fertilizers in farms characterized by high feed self-sufficiency, compared to those farms characterized by lower levels of feed self-sufficiency. This can again be explained by the larger amounts of feeds produced on the farm UAA which led to a lower amount of purchased feeds and a higher level of inputs needed to grow crops on farm.

In the case of LO, farms characterized by higher levels of feed self-sufficiency showed a different trend in the contribution analysis of LO components, with a higher incidence of the farm size and a lower incidence of off-farm land required to grow purchased feeds. Nevertheless, the quality of land use should be taken into account, with annual arable crops, permanent pastures and multiannual meadows showing a different degree of competition with human nutrition (Garnett, 2009; Wilkinson and Lee, 2017) and a different degree of environmental services provided (Dumont *et al*., 2019). In this study an evaluation of the correlations between the technical efficiency indicators and environmental impacts has been made. Gains in productive efficiency allow increases in meat production to be made with reductions in the related environmental impacts. This can be achieved through the 'dilution of maintenance' effect described by Capper (2011), which encompasses the individual effects and the interactions among meat yield per animal, daily maintenance requirements, time from birth to slaughter, growth rate, genetic improvements, reproductive efficiency, age at first calving, replacement and mortality rates (Capper, 2011). The positive correlation between GWP and calving interval observed in this study is in agreement with the results of Vellinga *et al*. (2011) and Lopez-Pardes *et al*. (2018), who stated that working on the fertility performances of the herd could be an effective solution to reduce the environmental impacts of beef cattle. A good fertility in the herd allows a higher number of calves per year to be obtained from a fixed number of cows, thereby increasing the amount of available LW that can be sold. A short calving interval also means that a given number of calves can be obtained from a smaller number of suckler cows, thus reducing the enteric methane emissions and all the other input emissions related to suckler cows. Furthermore, a negative correlation was found between the number of heads of farm-born cattle sold per LU and all the environmental impact categories analysed (GWP, AP, CED and LO) highlighting the importance of optimized herd management (herd fertility and calf mortality for example) for the reduction of beef environmental impacts. Purchased concentrate consumption and concentrate self-sufficiency, as expected, showed a negative correlation, but it is interesting to note that concentrate self-sufficiency is positively linked with both fuel and mineral N use implying that a higher satisfaction of feed herd needs is counterbalanced by a higher use of external inputs for feed production on the farm surfaces. On the other hand, purchased concentrate consumption positively correlated with animal output per ha (kg LW/ha) highlighting the dependence of farms with high stocking rates on purchased concentrates to increase beef production. Given these relationships between environmental impacts and efficiency indices, the highest GWP values were observed in those farms characterized by poor efficiency performances, in the present study. As all the environmental indicators refer to the functional unit, it is clear that improving production efficiency at every level (crop, herd, animal, and farm) is a key point for the reduction of the environmental impacts of beef production (Beukes *et al*., 2010; Taylor *et al*., 2020).

It has been recognized that the main driver of livestock GHG emissions is the production efficiency (resource input per unit of product output), as reported by Capper (2011). In view of adapting mitigation strategies at a system-wide scale, it seems appropriate, from the findings of this study, that farm land should be managed to best meet the needs of the herd (reducing transport-related and LUC emissions), especially protein needs, and increase overall farm self-sufficiency. The first option to increase self-sufficiency is represented by the direct use of on farm-grown grains as animal feeds instead of selling these grains, as observed in several of the surveyed farms. An increase in farm self-sufficiency may also be achieved through the adoption of more efficient and resilient cropping systems, based on legume crops, the scheduling of forage cuts to early stages of growth, and the adoption of silage conservation (Tabacco *et al*., 2018). A further option could be the possibility of increasing the interrelationships between neighbouring farms by direct exchange of feeds and manure (Martin *et al*., 2016) to improve feed self-sufficiency and reduce the N excesses of intensive livestock farms (Peyraud *et al*., 2014). Relationships between technical efficiency indicators and environmental impacts have been found, suggesting that working on the fertility performances of the herd is a key point for the reduction of beef contribution to global warming (Taylor *et al*., 2020), thus positively contributing to the achievement of the Sustainable Development Goals of the Agenda 2030 (United Nations, 2015).

Conclusions

The Piedmontese beef production system has shown average environmental impacts comparable with those found for other farming and breeding systems. Between-farm differences have been detected, with positive environmental effects for improved fertility and animal productivity being observed. Moreover, the role of the valorisation of farm crop areas to meet most of the animals' needs has been underlined. Interesting results have emerged on the contribution analysis of contributing factors showing the high importance of purchased feeds, in particular protein feeds, transports and mineral fertilizers to the GWP of beef production. Furthermore, correlations have been found between environmental impacts and fertility-related indices showing that a good herd fertility is essential for suckler calf-to-beef farms to obtain high productive and environmental performances. Improved efficiency in resource use and herd management can help to reduce the issue of beef environmental impacts contributing to a potential positive effect from an economic (higher productivity) and food security (meet beef growing demand) perspective. These results indicate the need to work on these aspects with a holistic approach that links the cropping system to livestock rearing to reduce the environmental impacts of beef production.

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